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ARTICLE

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Examining the existing definitions of wildland-urban interface for California

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Abstract

Past studies reported a drastic growth in the wildland–urban interface (WUI), the location where man-made structures meet or overlap wildland vegetation. Fighting fire is difficult in the WUI due to the combination of wildland and structural fuels, and therefore, WUI areas are characterized by frequent damage and loss of structures from wildfires. Recent wildland fire policy has targeted fire prevention, evacuation planning, fuel treatment, and home hardening in WUI areas. Therefore, it is important to understand the occurrence of wildfire events relative to the location of the WUI. In this work, we have reported the occurrences of wildfires with respect to the WUI and quantified how much of the WUI is on complex topography in California, which intensifies fire behavior and complicates fire suppression. We have additionally analyzed the relative importance of WUI-related parameters, such as housing density, vegetation density, and distance to wildfires, as well as topographic factors, such as slope, elevation, aspect, and surface roughness, on the occurrence of large and small wildfires and the burned area of large wildfires near the WUI. We found that a very small percentage of wildfire ignition points and large wildfire-burned areas (>400 ha or 1000 acres) were located in the WUI areas. A small percentage of large wildfires were encountered in WUI (3%), and the WUI area accounted for only 4% of the area burned, which increased to 5% and 56%, respectively, outside WUI (5-km buffer from WUI). Similarly, 66% of fires ignited outside WUI, whereas only 3.6% ignited within WUI. Results from this study have implications for fuel management and infrastructure hardening, as well as for fire suppression and community response.

KEYWORDS
buffer distance, complex topography, firebrands, wildfires, wildland–urban interface, WUI

INTRODUCTION

The intensity and frequency of wildland fires over the contiguous United States (CONUS) have been increasing remarkably and have caused much economic damages in the last two decades (Bowman et al., 2009; Massada et al., 2009; Radeloff et al., 2018). The damages due to these extreme events are mainly located at wildland–urban interfaces (WUI), which are regions where houses and man-made structures meet or overlap the wildland vegetation as defined in the Federal Register (US Department of Interior and the US Department of Agriculture), 2001. The current definition of WUI includes the concepts of "intermix" and "interface." "Intermix" is the area where human developments and wildland vegetation overlap, whereas "interface" is that region which is nearby to a densely vegetated wildland. This definition of WUI is in concurrence with the National Fire Plan (NFP), which was based on the WUI fire risk report (Teie, 1999). This framework consists of the following three main parameters: (1) housing density threshold of 6.18 houses/km^2 (1 house/16.2 ha or 40 acres), (2) vegetation type, and (3) proximity of 2.4 km (1.5 miles) from dense vegetation (over an area of 5 km^2 with >75% vegetation cover). Out of these three parameters, the housing density threshold is the most sensitive parameter in the existing definition of WUI as studied by Stewart et al. (2007) and Radeloff, Hammer, Stewart, Fried, et al. (2005). Earlier definitions of WUI were centered on the metric of population density (Glickman & Babbitt, 2001). However, it was later recognized by Liu et al. (2003) that housing density was a more appropriate metric compared to population density for mapping WUI. Therefore, the WUI criteria had been modified, and the housing density threshold was included in the WUI definition in the Federal Register (2001) for WUIs (for both intermix and interface).

Several earlier studies had been devoted to analyze the expansion of WUI areas across North America over the past several decades and the drivers behind it. A few studies (Johnson et al., 2005; Radeloff et al., 2001) identified the cultural aspect of the human inclination to live near the natural amenities provided by forested lands, mountainous regions, and seashores. Housing growth was widespread in rural and suburban areas in the United States during the mid-1900s. Its continued trend contributed to a 41% growth in the construction of new homes within the WUI from 1990 to 2010 (Radeloff et al., 2018; Radeloff, Hammer, & Stewart, 2005). Housing density has grown faster than population density in recent decades, and the same trend is reflected in the context of WUI (Martinuzzi et al., 2015). Also, more than 50% houses present in the WUI were damaged in California due to large wildfires (Caggiano et al., 2020). Thus, there is a higher risk of structural damage due to wildfires in the WUI.

The existence of the WUI terminology was already in place before the wildland fire policies had taken it into consideration in the 2000s, but it was not as widespread in the wildfire literature. It had only become a widely used term in recent years due to the increasing/maximum damages in this land-use type due to wildfires (Martinuzzi et al., 2015; Radeloff et al., 2018). Vaux (1982) discussed future risks due to the emerging interface areas and called WUI the "hotseat of forestry." Also, Bradley (1984) focused on this new interface in their famous book on resource management, but none of them had related WUI with wildfires. Finally, Davis (1990) connected the idea of WUI with the wildland fires. Currently, the term WUI is used mostly in the context of wildfires as the maximum damages due to wildfires occur in the WUI (Kramer et al., 2019). Stewart et al. (2009) demonstrated that WUI definitions vary depending on purpose and context by comparing the two definitions that are based on the NFP and Healthy Forest Restoration Act (HFRA) with the study location over the Los Angeles area. The NFP definition had focused on the number of structures (housing-centric definition) nearby the wildland vegetation within a buffer of 2.4 km (1.5 miles) for the interfaces, and, therefore, it was more helpful to the policymakers in determining the risk-prone housing regions and taking possible steps in reducing the growth rate of the homes in these locations. According to the California Fire Alliance (2001), on an average, a firebrand can travel up to 2.4 km from a wildland fire front, and thus the buffer distance for the interface is the same. The houses within this buffer zone would be at a higher risk of burning during wildfire events. On the other hand, the HFRA definition of WUI was more helpful to the land managers and has the aim of finding the sources of fuels for future wildfires within the vicinity of the houses/structures and therefore can be considered a fuel-centric definition. The HFRA defined interfaces that are present within a buffer of 805 m (0.5 miles) from the houses and called it a mitigation zone for the Community Wildfire Protection Plans (Wilmer & Aplet, 2005).

Apart from these many existing definitions of WUI, a new WUI mapping called Fire and Resource Assessment Program (FRAP) was developed by California Department of Forestry and Fire Protection (CAL FIRE), the agency to serve and safeguard the people and protect the property and resources of California. The FRAP modified the definition of WUIs (intermix and interface) in terms of the housing density thresholds in concurrence with the NFP policy and mapped it for California for 2010. Platt (2010) compared five different WUI models, including FRAP, based on the choice of wildland vegetation, housing density with and without public lands, buffer distance from wildland vegetation or human settlements and its magnitude, as well as the point- and zonal-based approaches of defining housing density. It was found that the WUI mapping methods were characterized by different degrees of accuracy, which vary with their utilization and extent of study (Stewart et al., 2009). For example, in the point-based approach of defining housing density, structures were represented as points and mapped from the parcel centroid, excluding remote buildings, which were farther than 569 m (0.35 miles) from another building (Platt, 2010). Many other WUI definitions (Pereira et al., 2018) were based on different data sources, such as remote sensing, census block, or their combination. Furthermore, there were different WUI mapping methodologies based on purpose, for example, housing centric and fuel centric, as mentioned in Platt (2010). However, none of the studies analyzed and compared the predominant definitions of WUI with the context of wildfire occurrence.

Syphard et al. (2019) demonstrated the impact of climate change and urbanization on the loss of buildings in California. They quantified that building losses are high in low-density buildings and that with housing development, it might further increase. Kramer et al. (2019) also highlighted that more destructive wildfires threatened and damaged more buildings in the interface WUI and fewer in rural regions. Also, the rate of building destruction is higher in urban areas where there is a higher population density than in rural areas. They reported that in the last three decades, 50% of buildings destroyed in California were at WUI interfaces and 32% of buildings destroyed were in WUI intermix areas (Kramer et al., 2019). On an annual basis in the WUI (1999–2014), an average of 2.5 million homes (2.2–2.8 million, 95% confidence interval) were threatened by human-started wildfires (within the perimeter and up to 1 km away), as reported in a recent study by Mietkiewicz et al. (2020). Therefore, increasing trends in the expansion of WUI areas would mean that more lives and properties are at risk from wildfire-induced damage.

Wildfire events have been increasing within the WUI in the CONUS (Martinuzzi et al., 2015; Platt, 2010). In California, the frequency of even smaller fires (<202.3 ha or 500 acres) caused by human activities has increased from 2010 to 2019 (Li & Banerjee, 2021). The wildfire ignitions are also directly proportional to the WUI expansion (Syphard et al., 2019). The proportion of buildings destroyed within the WUI and non-WUI zones was 69% and 31%, respectively, in the United States (Kramer et al., 2018). However, on overlapping the area of fire perimeters with the building footprints from 2000 to 2013, only 1.1% (1398 km^2) of the buildings were destroyed within the WUI, whereas this number was 34% (41,262 km^2) within the non-WUI regions in the United States (Kramer et al., 2018). Caggiano et al. (2020) highlighted that more than 85% building losses occurred in the WUI due to wildfires from 2010 to 2018. However, out of a total of 2777 fires, only 70 were used in this study (Caggiano et al., 2020), which damaged more than 50 buildings and were called WUI disasters.

Fighting fire is difficult in the WUI due to the unique combination of wildland and structural fuels, as firefighters are usually trained in either wildland fires or structural fires but not both (Stewart et al., 2003). Moreover, wildfire exposure threatens or undermines the community and ecosystem services provided by WUI areas, such as enjoying recreational activities, timber production, habitat conservation for several species, watershed protection, and even visual aspects, such as scenic beauty (Stewart et al., 2003). Thereby, it is important to understand the modes of fire exposure at the WUI, which would impact both aspects of fire prevention, suppression, and fire impacts on the WUI. Recent wildland fire policy has targeted fire prevention, evacuation planning, fuel treatment, and home hardening against ignition in WUI areas (Cohen, 2000; Haight et al., 2004; Radeloff et al., 2018; Radeloff, Hammer, Stewart, Fried, et al., 2005). Therefore, it is important to understand the occurrence of wildfires relative to the WUI areas as well as the relative importance of WUI-related factors that influence wildfire occurrence and size.

Moreover, in states like California (and many of the western states in the United States), a significant area of the WUI might be situated on complex topography. If the presence of the WUI is generally perceived to be associated with heightened fire risk, it is worth knowing how much of the WUI is on complex topography. This is important from a planning and policy perspective, given that firefighting, rescue, and evacuation operations are significantly complicated due to the presence of complex topography. The presence of topography adds to uncertainties in wildfire behavior (Linn et al., 2007) and leads to the creation of micrometeorological conditions, which change the wind patterns and turbulence levels in the atmospheric boundary layer over the WUI. This orographic effect might lead to differences in how far firebrands can travel and where they land compared to flat terrain. Therefore, relying on a buffer zone of 2.4 km from a densely vegetated area as a general criterion is worth analyzing further. Graham et al. (2012) showed very interesting results that embers are not the only cause of ignition away from the ignition points and low-intensity surface fires can also lead to significant damages. However, there is always a higher risk of ignition within the fire perimeter than outside it because of the close vicinity to the flame front. Overlapping past wildfire events with WUI along with complex topography would help us understand where wildfires occur relative to the WUI areas, thereby providing a quantified measure of the perceived risk associated with the wildfire–WUI connection.

In this work, our objectives are the following: (1) evaluate the two predominant definitions of WUI against the actual occurrences of wildfires in CA; (2) examine the role of the parameters used to define the WUI, such as the buffer distance, in determining the relationship between wildfire occurrence and WUI; (3) evaluate if the presence of complex terrain is an important factor in the WUI, as complex topography might mean more complex rescue, firefighting, and evacuation operations, and the presence of complex terrain means further uncertainty in parameters, such as buffer distance, since they are based on ember transport characteristics; and (4) evaluate the relative importance of parameters that define the WUI in wildfire occurrence within or near the WUI. To satisfy these objectives, we will attempt to answer the following research questions.

1. Where are the wildfires (a) igniting and (b) burning relative to the WUI?
2. What is the impact of buffer distance on the percentage overlap of fire perimeters and fire ignition points in the WUI?
3. Where is the WUI located in terms of elevation and the complexity of the terrain?
4. What is the relative importance of WUI parameters that impact wildfire occurrence and size within or near the WUI?

Results from this paper will be helpful for wildfire management and would benefit policymakers and land managers at the state and local levels to focus on the factors that determine the high-risk-prone areas for future wildfires.

MATERIALS AND METHODS

WUI data

We used two existing WUI data sources for 2010 that were obtained from United States Forest Service (USFS) (Martinuzzi et al., 2015) and CAL FIRE (FRAP, 2015). We designate them WUI-A and WUI-B, respectively, for our study. We plotted a spatial map of WUIs over CA to analyze the variation in the location of the WUI, which includes both the WUI intermix and the WUI interface. WUI-A used the definition of Federal Register (2001) following the NFP policy, whereas CAL FIRE modified the housing threshold and added the wildfire influence zone and moderate or higher levels of fire hazard severity zones (FHSZ).

Wildfire data

Since we wanted to overlap wildfire datasets with WUI, which was from 2010, we could not choose those wildfires that occurred before 2010 to overlap with 2010 WUI data. Perimeters of wildfire events were obtained from the Monitoring Trends in Burn Severity (MTBS) dataset (MTBS, 2020) that includes all fires (2010–2017) in CA having an area of >400 ha (1000 acres). We designate these wildfires as large wildfires (Butry et al., 2008). Landsat imagery of prefire and postfire images at a resolution of 30 was used by Eidenshink et al. (2007) to detect MTBS fire perimeters, which reflect the boundary of the region burned by a wildfire event. The wildfire data obtained from MTBS for CA have a total area of 19,517.675 km^2 of wildfires from 2010 to 2017. They also comprise a total of 329 fire ignition points in the state from 2010 to 2017. Also, the fire ignition point data are consistent with the wildfire perimeter datasets. Ignition points of the fires were obtained from MTBS Fire Occurrence Points (Scott et al., 2016) for 8 years, that is, from 2010 to 2017 (MTBS, 2020). The National Wildfire Coordinating Group classified wildfires into seven classes, ranging from A to G, based on their size. In this study, we defined classes A–E as small fires or wildfires with an extent of <400 ha (1000 acres). The thresholds for large and small wildfires were determined with reference to the research of Butry et al. (2008). Small wildfire (<400 ha) points were obtained from the fifth edition of spatial wildfire occurrence data originated by Short (2021). It collected wildfires from 0.001 acre across the United States from 1992 to 2018. Wildfires in California that are smaller than 400 ha (1000 acres) were extracted from this database and defined as small wildfires in this study.

County and topography data

County boundaries for the state of California have been taken from the CA government geographic boundary (County Boundary, 2019). Elevation data were obtained from Google Earth Engine (GEE), which used United States Geological Survey Digital Elevation Map (DEM) elevation maps available at 1/30 arc-second (GEE, 2012). For our study, we resampled the obtained data from GEE at a spatial resolution of 10–30 m using the ArcMap (10.7.1) tool in ArcGIS (2020). To calculate the overlap of 2010 WUI and different elevation ranges, we used the ArcMap 10.7.1 (ArcGIS, 2020) spatial analyst tool, selected the extraction tool, and then chose extraction by mask. First, we reclassified the elevation data into nine separate ranges: The first eight ranges were from 0 to 800 m in 100-m intervals, whereas the last range was from 800 to 4410 m. Then, we merged both WUI-A and WUI-B with these ranges to calculate the number of counts falling in each elevation range. Moreover, we made sure that WUI and elevation raster layers have the same properties. WUI-A data available in vector form were converted to raster using ArcPy (ArcGIS with Python), keeping the same 30-m spatial resolution as the elevation data. We then divided the number of counts in each elevation range by the total count to find the percentage WUI over different elevation ranges. We performed similar methods for calculating the percentage overlap of WUI and elevation for CA with both WUI-A and WUI-B for the year 2010.

To see the surface roughness for the state that has numerous mountains and complex topography, we have calculated the rugosity of this region, which is defined as the ratio of actual surface area to the planar surface area of a region. A higher value of rugosity shows the presence of more complex terrain in that region and vice versa. We have used the DEM surface tool developed by Jenness (2004) in the ArcMap to calculate the rugosity (surface ratio) for the state. The DEM surface tool has one advantage over other existing surface ratio calculation tools. Here, we do not need to do adjustment in Z-units with respect to X/Y units while dealing with data in geographic coordinate systems. Otherwise, we need to get the Z-units corrected first to calculate the surface ratio. The WUIs (both WUI-A and WUI-B) have overlapped with rugosity following the same methodology as discussed above for elevation to find its variation with surface roughness for the state.

Analysis methods

The overlap of wildfire perimeters and WUI has been processed in ArcGIS with varying buffer distances using the buffer tool in geoprocessing, followed by the dissolve tool to merge each buffer into one feature. Five different buffer radii from 1 to 5 km have been selected around wildfire perimeters and WUI (both WUI-A and WUI-B). WUI-A data were available in polygon (vector), so WUI-B raster data were converted to polygon using conversion tools in ArcMAP. Finally, we intersected fire perimeters (WUI buffers) and WUI (fire perimeter buffers) to obtain the overlapped area. For the calculation of fire ignition points within WUI buffers, we have used “select by location” using the selection method as “select from layer” and choosing the target layer as fire ignition points and the source layer as WUI buffer layers (WUI-A and WUI-B).

Statistical models

To model the relationship among wildfire presence, wildfire area, distance from wildfires to WUIs, housing density, and vegetation density, the logistic regression model (LoR) was applied. The dependent variables in the model are the probability of wildfire occurrence (including both large and small wildfires) and large wildfire areas. It is noted again that for wildfire occurrence, data from both large and small wildfires are available as discussed above, whereas for burned area, only the data for large wildfires (>400 ha) are available and considered. The ignition points of wildfires extracted from MTBS were assigned a value of 1. Then, as many random points as wildfire points were generated within the boundary of California and out of the large wildfire perimeters. These points were assigned a value of 0, which means there were no large wildfires from 2010 to 2017. The independent variables in this model included distance from wildfires to WUI-A and WUI-B, which was calculated using the “near” function in ArcGIS Pro; housing density, calculated using 2010 census data; vegetation density, calculated using fuel vegetation cover from LANDFIRE; and topographic information, including elevation, aspect, slope, and rugosity. The area under the receiver-operating characteristic curve of the LoR model is the probability of a large wildfire occurrence with a range of 0–1. The probability higher than 0.5 represents a strong correlation. When there is more than one independent variable in the model, the estimated coefficients represent the change in the log odds of a large wildfire occurrence per unit change in the independent variables. The results table also included the standard error, z statistics, and associated p values in model fitting.

RESULTS AND DISCUSSION

Difference between two types of WUI mappings for California

The definition of WUI varies with different mapping methods and the changes in the major parameters, like housing density threshold and buffer distance. Figure 1 shows the differences in the WUI distribution for California as mapped by USFS (Martinuzzi et al., 2015) and CAL FIRE (FRAP, 2015) for the year 2010. The housing density threshold used by these two mappings is different and is 6.18 houses/km^2 (1 house/16.187 ha or 40 acres) in the former, whereas it is >1 house/0.08 km^2 (>1 house/8 ha or 19.8 acres) in the latter. CAL FIRE also includes other parameters for the WUI definition and requires moderate to very high FHSZ. (The FHSZ were defined by CAL FIRE to evaluate “the severity of fire hazard that is expected to prevail there” based on various factors, such as fuel, slope, and fire weather.) In addition, their definition warrants spatially contiguous groups of 30-m cells having an area larger than 0.04 km^2 (4 ha) for the WUI interface and larger than 0.1 km^2 (10 ha) for the

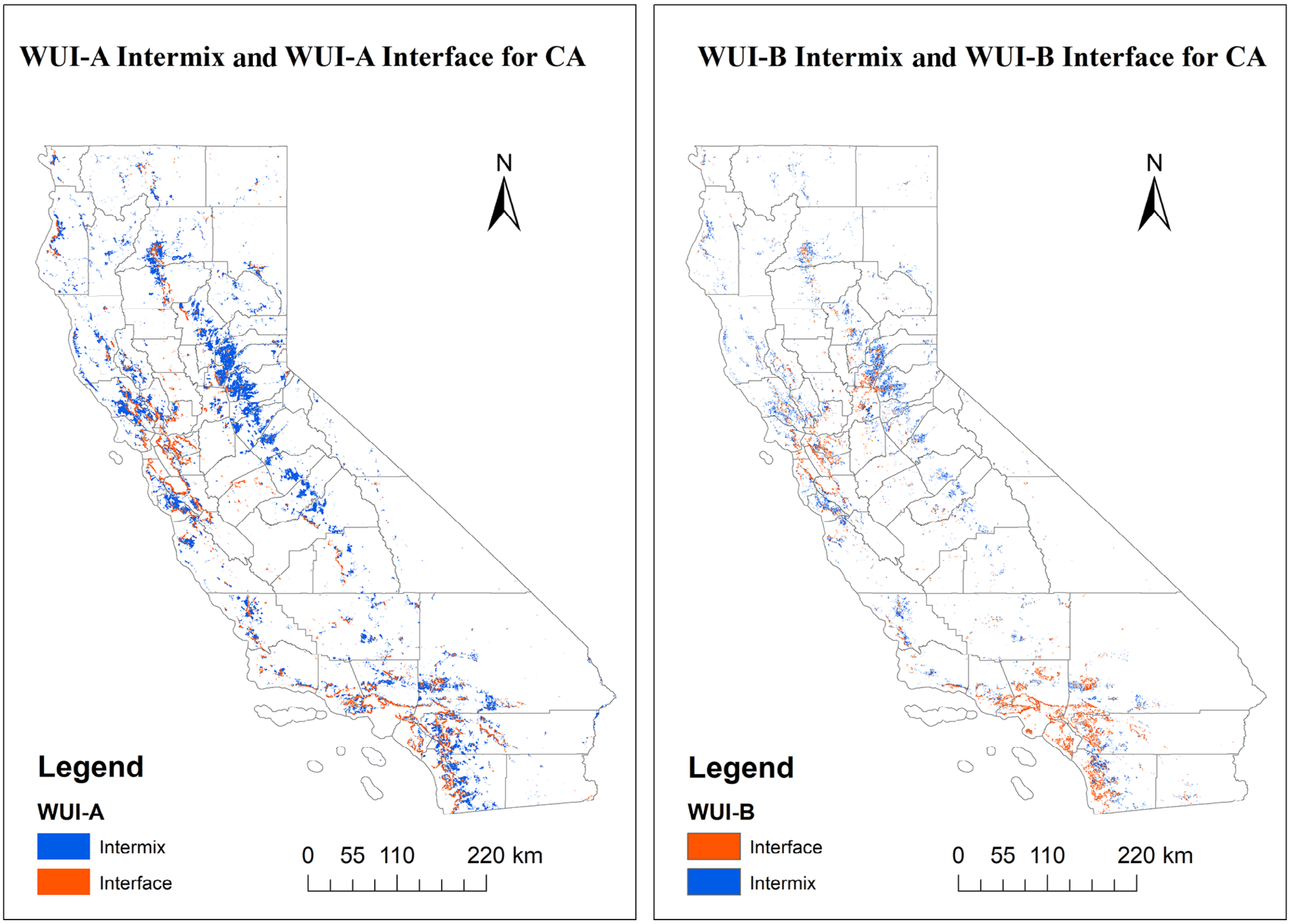


FIGURE 1 Spatial plots of wildland–urban interface (WUI) in 2010 over California using WUI data from United States Forest Service (Martinuzzi et al., 2015) and CAL FIRE (FRAP, 2015) designated as WUI-A and WUI-B, respectively. "Intermix" represents the area where human developments and wildland vegetation overlap, whereas "interface" is that region that is nearby to a densely vegetated wildland.

WUI intermix. Although the buffer distance of 2.4 km (1.5 miles) is the same in both the cases; for WUI-A, it is the distance from a densely vegetated area and is called WUI intermix, whereas for WUI-B, it is the distance up to which flammable vegetation lies from WUI intermix or WUI interface and is known as the wildfire influence zone. WUI-A consists of more area (27,025.683 km^2) than WUI-B (9606.273 km^2), as shown in Figure 1, because of the difference in the housing thresholds and additional vegetation classification parameters used for WUI-B. The overlapping results between WUIs and wildfires are similar for both types of WUIs (WUI-A and WUI-B), where intermixes have a higher percentage overlap than interfaces (Table 1).

Overlap of WUI with wildfire-burned areas

The wildfire data used in this study, obtained from MTBS, report a total burned area of 19,517.675 km^2 for CA. These historical wildfire datasets are from 2010 to 2017 and include all fire events with burned areas of >400 ha (1000 acres or 4 km^2). Table 1 shows the total area of WUI-A in CA to be 27,025.683 km^2 with both the interface (8046.643 km^2) and intermix (18,979.040 km^2) types of WUI-A. The WUI-A interface has less (49.387 km^2) overlap between wildfire-burned areas and WUI-A than the WUI-A intermix (747.113 km^2). The percentage of overlap in wildfire-burned areas in the intermix WUI-A (3.83%) is higher than that in the interface WUI-A (0.25%), making a total of almost 4.1% of wildfire areas that burned within WUI-A. Note that these (aforementioned) percentages are computed as compared to the total wildfire-burned areas (i.e., overlap area/wildfire-burned area). The percentage of overlap between WUI areas and wildfire-burned areas can also be computed relative to the area of WUI itself (overlap area/WUI area shown in the rightmost column in Table 1). From this perspective, the percentage overlap in the WUI-A intermix is 3.94%, that is, more than six times the

TABLE 1 Overlap between wildfire-burned areas and fire ignition points with wildland–urban interface (WUI)-A and WUI-B.

Site type	Area (km^2)	Wildfire-burned area (km^2)	Overlapping area (km^2)	Percentage overlap[a]	Percentage of wildfires ignited	Percentage of overlapped area
(a) WUI-A		19,517.68				
Interface	8046.64		49.39	0.25	0.30 (1/329)	0.61
Intermix	18,979.04		747.11	3.83	3.34 (11/329)	3.94
Total	27,025.68		796.50	4.08	3.65 (12/329)	2.95
(b) WUI-B		19,517.68				
Interface	4232.85		24.43	0.13	1.22 (4/329)	0.58
Intermix	5373.43		129.17	0.66	0 (0/329)	2.40
Without influence zone	9606.27		153.60	0.79	1.22 (4/329)	1.60

[a] In wildfire-burned area.

overlap in the WUI-A interface (0.61%). Therefore, only 2.947% of WUI-A areas have been directly burned by wildfires during this study period.

Table 1 also shows the total area of WUI-B in CA to be 9606.273 km^2 with a lower proportion of the WUI-B interface (4232.847 km^2) than the WUI-B intermix (5373.426 km^2). Clearly, the percentage of overlap between the WUI-B interface and the wildfire perimeters relative to wildfire-burned areas is lower (0.125%) than intermix WUI-B (0.662%) for the state. Hence, only 0.79% of wildfire-burned areas are contained within WUI-B in CA. When the overlapped area is expressed relative to WUI-B areas, there is a higher percentage overlap in the WUI-B intermixes (2.4%) compared to the WUI-B interfaces (0.58%). Therefore, only 1.6% of WUI-B in CA has burned directly during the study period. Moreover, the intermixes have more wildfire-burned area than interfaces for both types of WUIs. The percentage overlap of wildfire-burned areas with respect to WUI areas is less for WUI-B (1.6%) as compared to WUI-A (2.95%) because of the exclusion of the influence zone from WUI-B definition (Figure 1).

Analysis of buffer distance from wildfire perimeters

From the discussion above, it is clear that a very small percentage of wildfires burn within the WUI areas in CA. This invokes the question of whether these wildfires burn in the vicinity of the WUI areas. To investigate the occurrence of wildland fires outside and away from the existing WUIs, we performed a buffer analysis, varying the distance from 1 to 5 km from wildfire-burned areas (Appendix S1: Table S2) and recalculating the previous statistics reported in Table 1. Appendix S1: Table S1 shows an increase in the percentage overlap of wildfire-burned areas and WUI-A with buffer distance relative to the wildfire buffer area (fifth column) and relative to the WUI area (sixth column). When the buffer radius increased from 0 to 5 km around the wildfire-burned areas, the overlapped region increased by more than nine times (from 796.5 to 7580.4 km). The percentage of this overlapped region in the WUI-A increased from almost 3% (for no buffer) to 28% (for a 5-km buffer distance). On the other hand, we observed a small change of only 4% in the percentage overlap in wildfire buffers by increasing the buffer distance from 0 to 5 km. This is expected because the wildfire buffer area relative to which the percentages are calculated also increases with the buffer distance. Similarly, the percentage overlap relative to WUI-B (sixth column) increased to 25.5% (Appendix S1: Table S1) with a 5-km buffer distance from wildfire-burned areas. On the other hand, the increase in the percentage of overlap relative to the wildfire buffers is from 0.8% to 2.5% with no buffer to a 5-km buffer distance, respectively. However, the effects of WUI types on the percentage overlap are not different between WUI-A and WUI-B; increasing the buffer distance from wildfires increased the percentage overlap in both the WUIs (Appendix S1: Table S1).

Figure 2 shows the spatial distribution of overlap between varying buffer distances from the existing wildfire perimeters and two types of WUI used in this study (WUI-A and WUI-B). Wildfire perimeters are nearer to WUI-A, as shown in Figure 2 on the left panel, and thus will result in a higher percentage overlap between wildfire-burned area and WUI-A (also shown quantitatively in Appendix S1: Table S1). Also note that the total area of WUI-B (9606.273 km^2) is less than that of WUI-A (27,025.683 km^2). Figure 3 shows the percentage overlap with increasing buffer distance with respect to the WUI

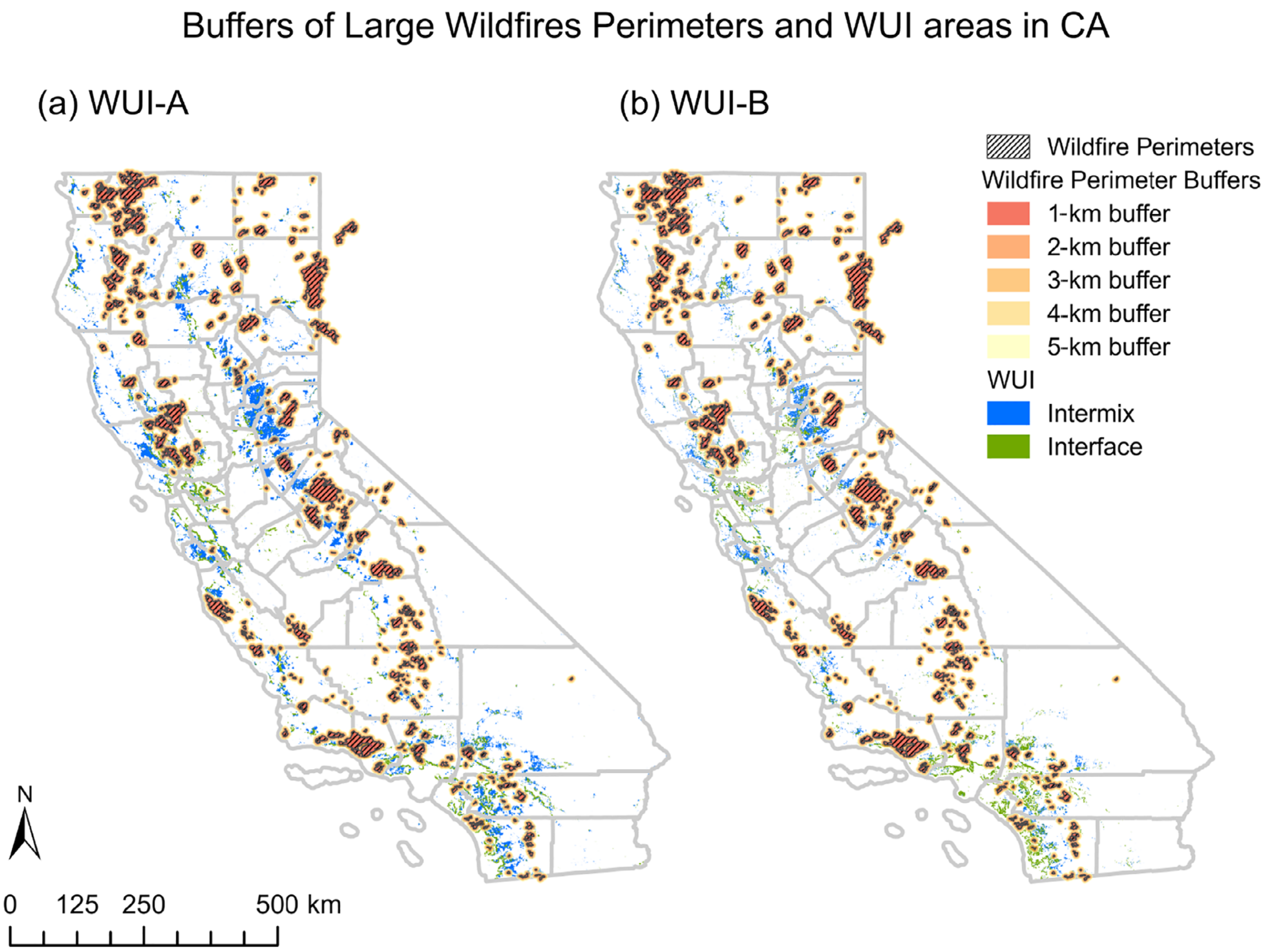


FIGURE 2 (a) Spatial plot of buffers of fire perimeters (large fires only, having an area >1000 acres or 400 ha) and wildland–urban interface (WUI)-A for CA; similarly, (b) buffers of large wildfires and WUI-B in CA. The legend shows the types of WUI (intermix and interface) and the varying wildfire perimeter buffer distances.

area in the red line and with respect to the wildfire buffer area in the black line. Both increasing trends are found to regress well with a linear trend. These linear trends are found for both WUI types. However, the slope in the case of WUI-B is higher as compared to WUI-A, and thus, there is a higher rate of increase in the percentage overlap. On the other hand, the percentage overlap with respect to wildfire buffer areas does not increase in a similar manner for both the cases with varying buffer distances. However, the rate of increase in percentage overlap in wildfire buffers is higher for WUI-B (from 0.8% to 2.6%) as compared to WUI-A (from 4% to almost 8%).

Analysis of buffer distance from WUI perimeters

In the previous section, the buffer distances were calculated from the wildfire perimeters. In this section, the buffer distances are calculated from the WUI perimeters, and similar statistics are calculated. The percentage overlap of wildfire-burned areas with varying buffer distances from WUI-A is shown in Appendix S1: Table S2 and depicted in Figure 4. The percentage of overlapped regions with respect to wildfire-burned areas (19,517.675 km^2) increased from 4% to 56% when the buffer distance from WUI-A changed from 0 to 5 km. Even with a buffer distance of 1 km, there is a 13% increase in the percentage overlap (from 4% to 17%), whereas the same overlapped areas with respect to WUI-A areas do not increase in percentage overlap (from 3% to 5%) with a 5-km buffer distance, given that the WUI buffer area also increases significantly (the denominator increases as well). Similarly, Appendix S1: Table S2 shows the overlap of wildfire-burned areas with varying buffer distances from WUI-B. The percentage overlapped with respect to wildfire perimeters increased up to 36% with a buffer distance of 5 km from almost

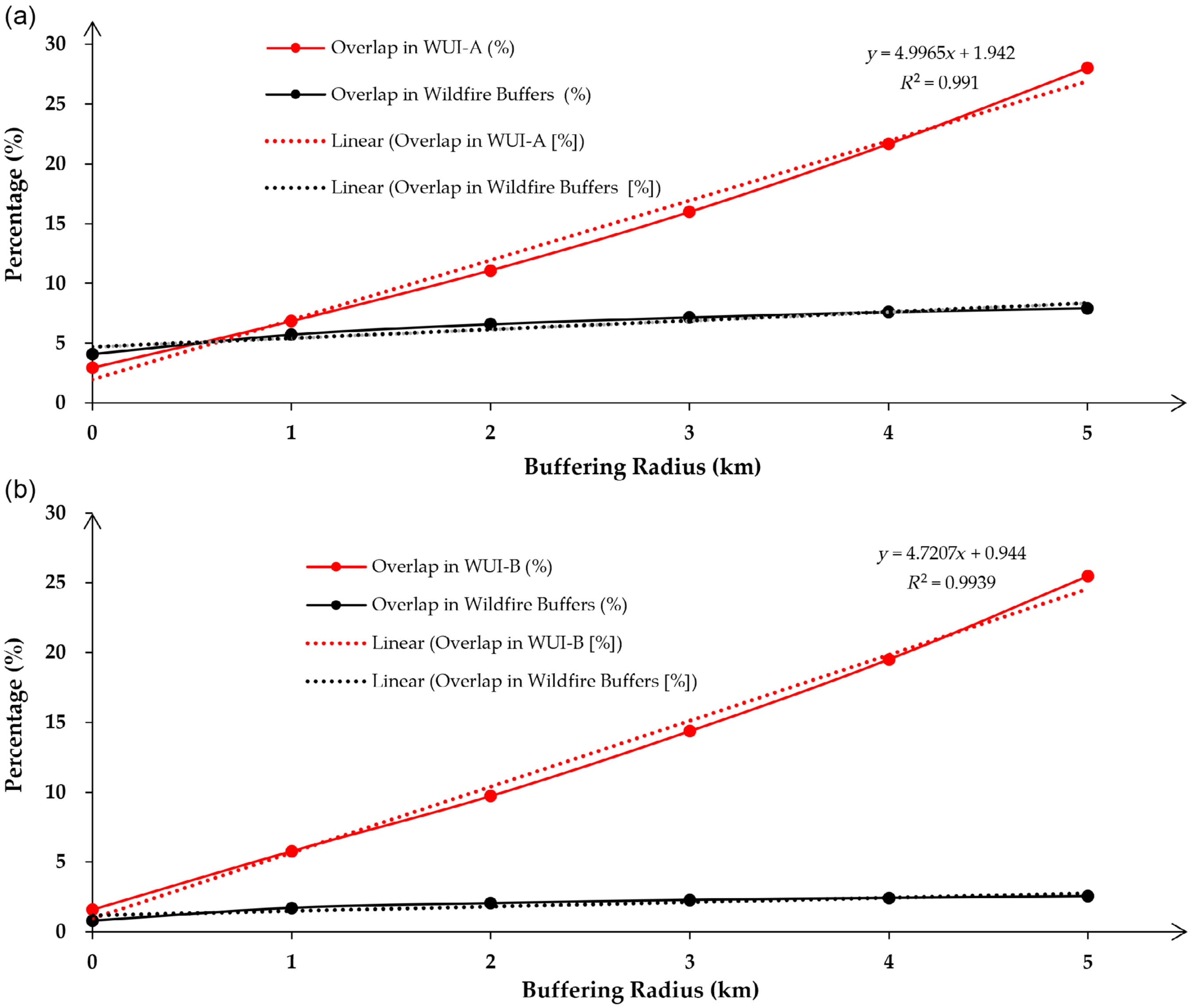


FIGURE 3 (a) Percentage overlap between wildfire-burned area with wildland–urban interface (WUI)-A with respect to WUI-A area (solid red line) and percentage overlap with respect to wildfire buffer area (solid black line). (b) The same for WUI-B. The dotted line indicates curve fitting (linear) for the percentage overlap in different types of WUIs (WUI-A and WUI-B).

0.8% overlap without a buffer around WUI-B, whereas the percentage overlap in WUI-B buffers did not increase in the same manner and changed to 4.2% from 1.6% with a 5-km buffer distance (again, due to the increase in the buffer area itself). Figure 5 shows that the percentage overlap with respect to wildfire perimeters increases linearly with buffer distance for both types of WUIs. However, the rate of increase in percentage overlap is higher in the case of WUI-A (top panel) as seen from the slope of the linear equation as compared to that of WUI-B (bottom panel). On the other hand, the percentage overlap with respect to WUI areas does not increase significantly for both cases.

Therefore, these results (Figures 4 and 5; Appendix S1: Table S2) give a clear visualization that wildfire events are not limited to the existing WUI but are more widespread outside it, that is, in the extended WUI. Fire risk maps associated with WUI areas should consider the buffer regions as well. These results also highlight how the two mapping approaches have different sensitivities to the proximity to wildfire events. The discussion above only considers fire perimeters, and it is worth asking whether fire ignitions also originate within or outside these WUI perimeters.

Overlap of WUI with fire ignition points for larger fires (>400 ha)

Table 1 shows that a total of 12 wildfires ignited in the WUI-A, of which only 8% (1 out of 12) occurred in the WUI-A interface and 92% (11 out of 12) ignited in

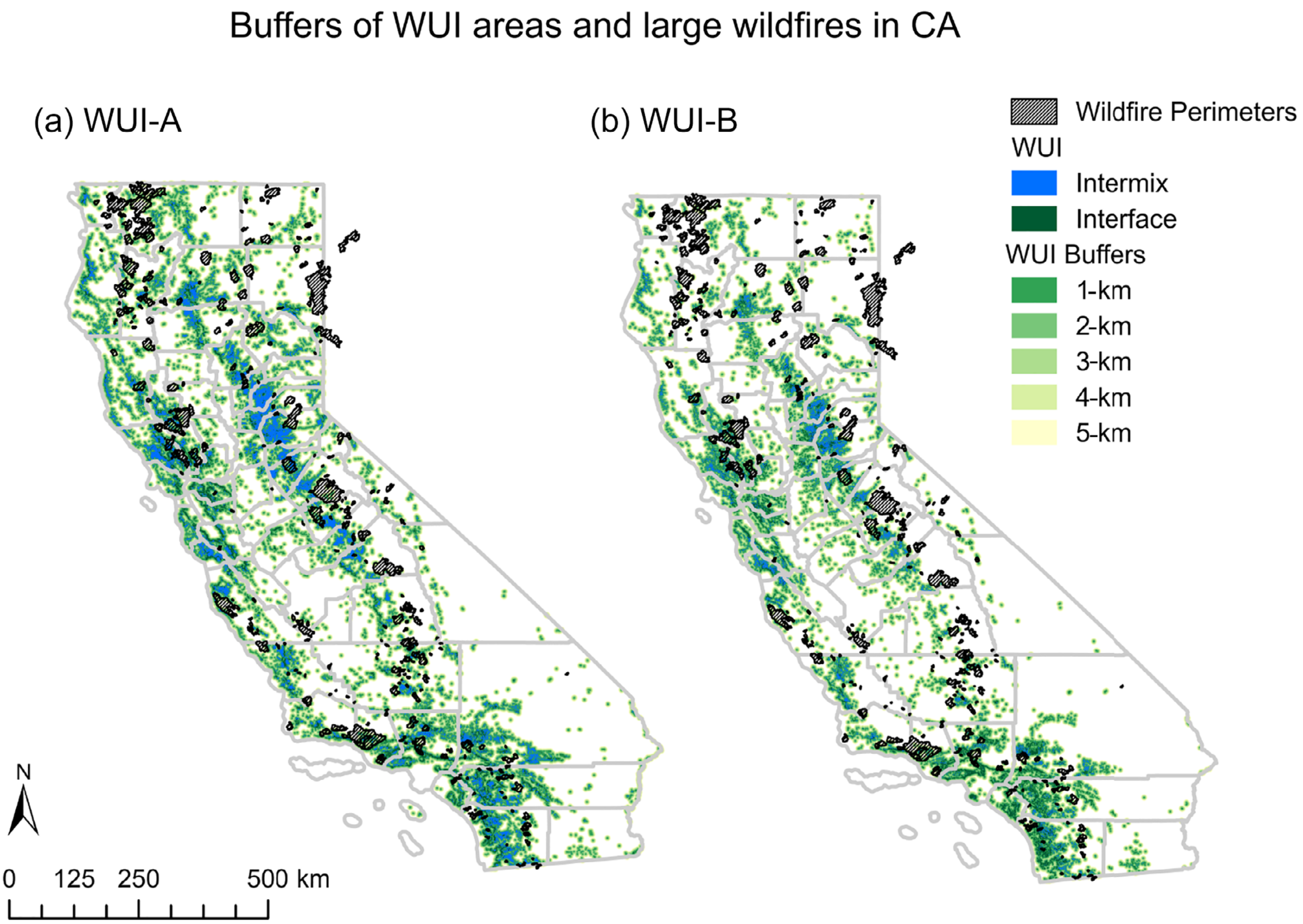


FIGURE 4 (a) Spatial plot of overlap of buffers of wildland–urban interface (WUI)-A with fire perimeters (large fires only, with area >1000 acres or 400 ha). (b) Spatial plot of overlap between buffers of WUI-B and fire perimeters (large fires only, with area >1000 acres or 400 ha). The legend shows the types of WUI, wildfire perimeters, and the areas of WUI-A and WUI-B with varying buffer distance from WUI. Overall, the percentage overlap between the buffers of the existing WUI and wildfire perimeters is higher in WUI-A than in WUI-B, and it increases in both the cases with increasing buffer radius.

the WUI-A intermix. On the other hand, only four wildfires ignited in the WUI-B out of 329 fires, and all of those occurred in the WUI-B interface, and zero fires ignited in the WUI-B intermix zone (Table 1). Thus, more wildfires ignited in WUI-A (3.6%) as compared to WUI-B (1.2%) in California. The percentage overlap of fire ignition points with varying buffer distance from WUI-A is shown in Appendix S1: Table S2 and plotted in Figure 5. Here, the number of wildfire ignition points within WUI-A increases drastically when the area of WUI-A increases with buffer distances. The number of ignition points was 72 out of 329 when there was a 1-km buffer around WUI-A, and it increased to 217 ignition points at a buffer radius of 5 km, making the percentage overlap to 66% from 22%. In addition, Figure 5 shows the logarithmic increase in the percentage overlap of fire ignition points within the WUI buffers. However, WUI-A (top panel) shows a higher rate of increase than WUI-B (bottom panel). Also, Appendix S1: Table S2 shows that the number of fire ignition points within WUI-B increases to 150 out of 329 (almost 46%) at a 5-km buffer radius as compared to 4 out of 329 ignition points (1.2%) within WUI-B buffers. Clearly, there is a noticeable increase in the number of fire ignition points falling in these WUIs (WUI-A and WUI-B) when the buffer radius increases from WUI. Therefore, our analysis shows that wildfire events do not occur in these predefined WUIs only, rather their frequency and burned area increase as we increase the buffer distance from existing WUIs.

Overlap of WUI with fire ignition points of smaller fires (<400 ha)

In our analysis with smaller fires (<1000 acres or 400 ha), we found that a total of 63,723 smaller wildfires ignited in the WUI, with only 32.42% of them igniting in

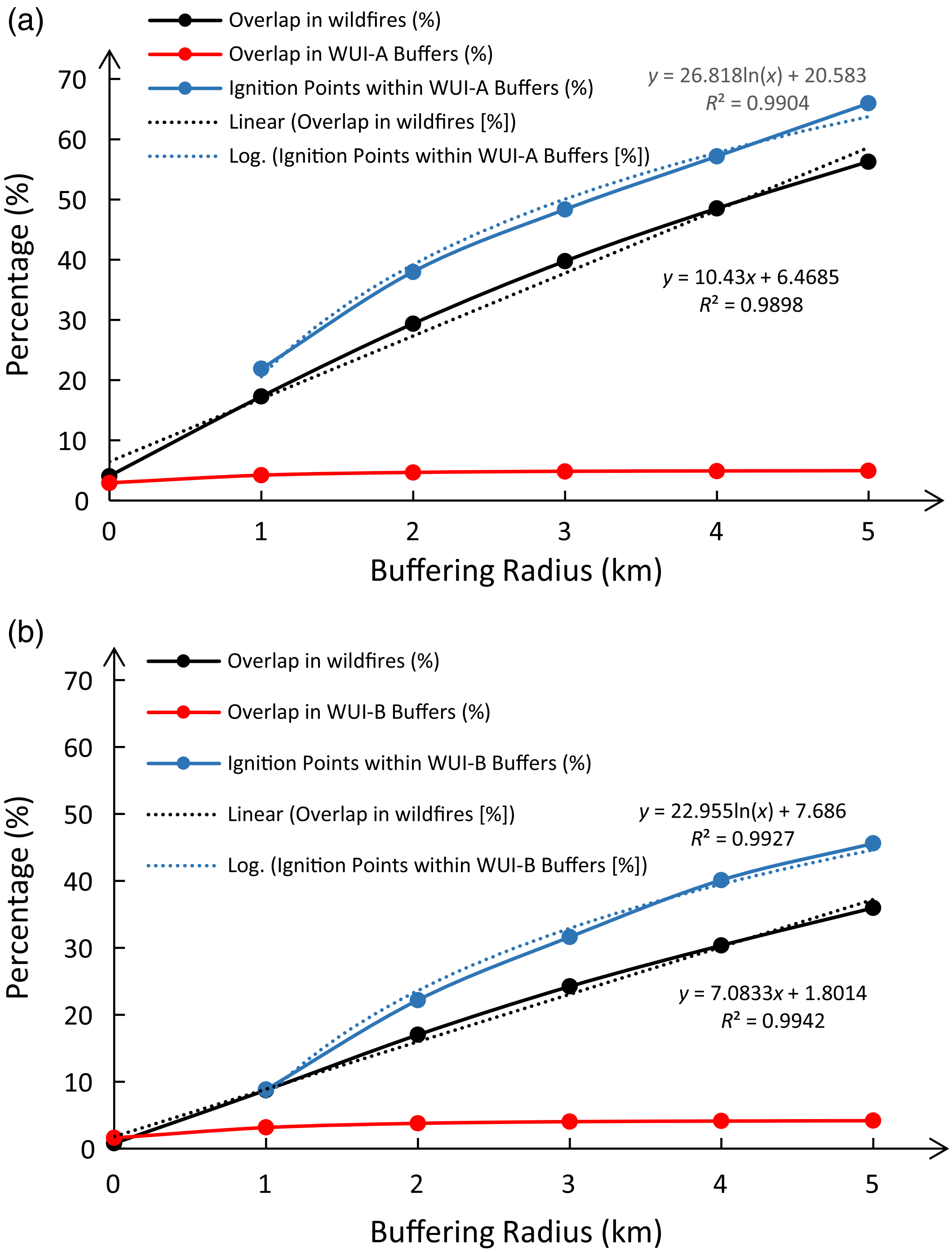
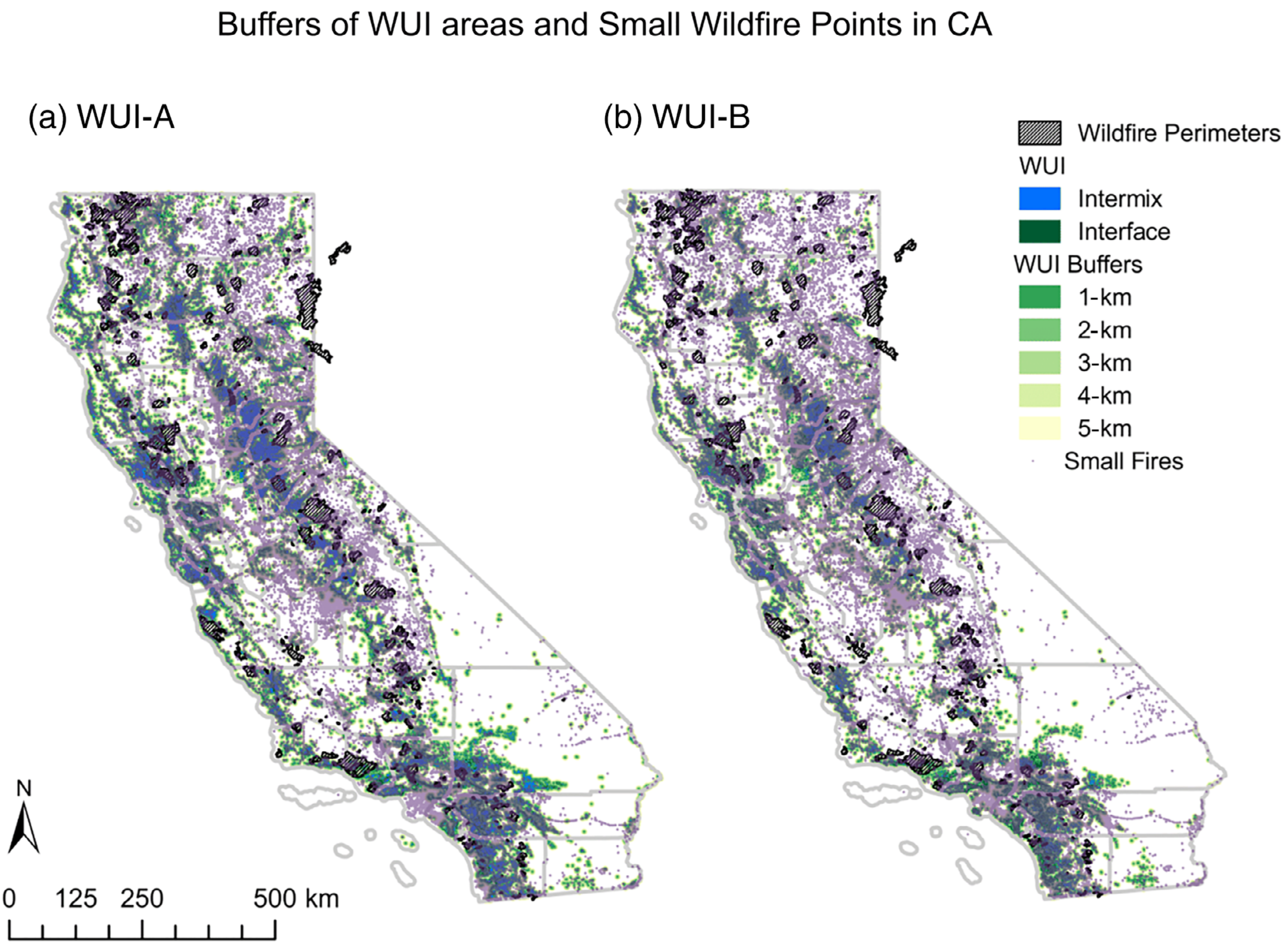


FIGURE 5 (a) Percentage overlap of wildfire-burned areas with wildland–urban interface (WUI)-A buffer areas. The solid red line represents the overlap with respect to the WUI-A buffer perimeters. Percentage overlap with respect to wildfire perimeters is shown by solid blue lines, and the fire ignition points within the WUI-A buffers are shown by solid black lines. (b) The same for WUI-B. The dotted line indicates linear curve fitting for the percentage of overlap in the area of wildfire perimeters and logarithmic curve fitting for fire ignition points within WUI buffers.

the WUI-A (Appendix S1: Table S7). In WUI-B, smaller fires ignited 18.51% (Appendix S1: Table S7). As a result, more wildfires erupted in WUI-A than in WUI-B in California. Appendix S1: Table S7 and Figure 6 show the percentage overlap of smaller fire ignition points with varying buffer distances from WUI-A. When the area of WUI-A increases with buffer distances, the number of wildfire ignition points within WUI-A increases. The percentage of ignition points within WUI buffers was 60.17% with a 1-km buffer radius around WUI-A and increased to 85.11% with a 5-km buffer radius. Figure 6 also depicts the linear increase in the percentage overlap of fire



(c) Percentage of small wildfires within WUI-A and WUI-B Buffers

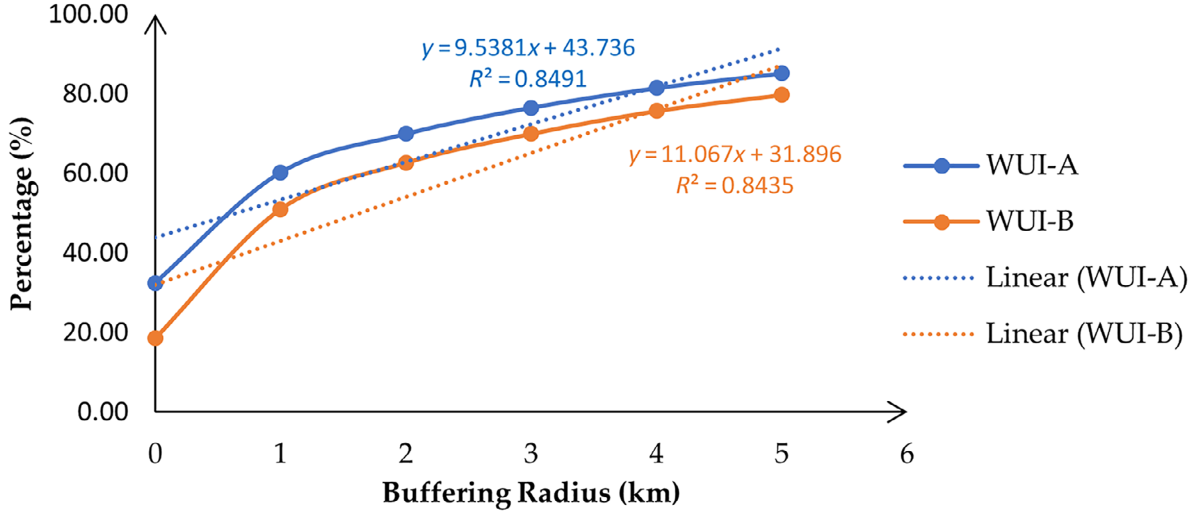


FIGURE 6 (a, b) Spatial plots of wildland–urban interface (WUI)-A and WUI-B in CA with the buffers of smaller wildfire ignition points (small fires only, having an area <1000 acres or 400 ha). The legend shows the types of WUI (intermix and interface) and the varying buffer distances surrounding WUIs. (c) Percentage overlap of smaller wildfire ignition points with WUI-A and WUI-B buffer areas. Percentage overlap with respect to the fire ignition points within the WUI buffers is shown by solid lines. The dotted line indicates linear curve fitting for smaller fire ignition points within WUI buffers.

ignition points within WUI buffers. Similarly, it also shows that the number of smaller wildfire ignition points within WUI-B increased to 79.70% at a 5-km buffer radius as compared to 50.96% at a 1-km buffer radius. Furthermore, we revealed that WUI-B has a higher rate of increase than WUI-A (Figure 6). When the buffer radius from WUI increases, the number of fire ignition points falling in these WUIs (WUI-A and WUI-B) significantly increases. As a result, this study demonstrates that even smaller wildfire events do not occur only in these predefined WUIs but that their frequency and burned area increase as the buffer distance from existing WUIs increases. It is interesting to note that only a small percentage of ignitions from both small and large wildfires start at the WUI, and the number of ignitions increases as we move further away from the WUI.

In the previous sections, the existing definitions of WUI have been discussed in the context of wildfire ignition and burned areas to investigate the risk of wildfires in the WUI. One of the three factors that influence fire risk and fire behavior is topography, namely slope, aspect, elevation, and surface roughness (along with fuel and weather). Therefore, whether the WUI areas in CA are strongly associated with complex topography is worth investigating to place the WUI fire risk into context, and this is discussed in the following section.

WUI on the complex topography

Elevation

Figure S2a in Appendix S1 shows the spatial distribution of elevation across CA, with a maximum elevation of 4410 m. Figure S1 in Appendix S1 shows the distribution of elevation ranges in CA. In Appendix S1: Table S3, we show the percentage overlap of WUI-A in 2010 with nine ranges of elevation for CA. The histogram plot (Figure 7a) shows that a significant WUI percentage lies in the elevation range of 0–100 m for WUI-B (20.17%) and above 800 m for WUI-A (21.4%).

Rugosity

Figure S2b in Appendix S1 shows the spatial distribution of surface roughness or rugosity over CA. In Figure 7b, an analysis of the percentage overlap between WUI areas and rugosity for CA yields an interesting outcome. It shows that only 0.4% of the WUI (WUI-A) are present on the regions with planar surfaces, having rugosity equal to 1. However, this number grows to 92.7% and 97.2% for WUI-A and WUI-B, respectively, for surfaces with rugosity values greater than 1 and less than or equal to 1.1 (Appendix S1: Table S4). A significant portion of the terrain (55% and 62% for WUI-A and WUI-B, respectively) is still situated on very low or moderate rugosity between 1.0 and 1.01. Moreover, it shows that almost 99.6% and 99.8% of the WUI-A and WUI-B, respectively, are in the nonplanar regions within CA. Therefore, a significant portion of the WUI in this state is located on mild to moderately rough terrain where the fire spread rate is higher than the flat surface and controlling large fires are more difficult.

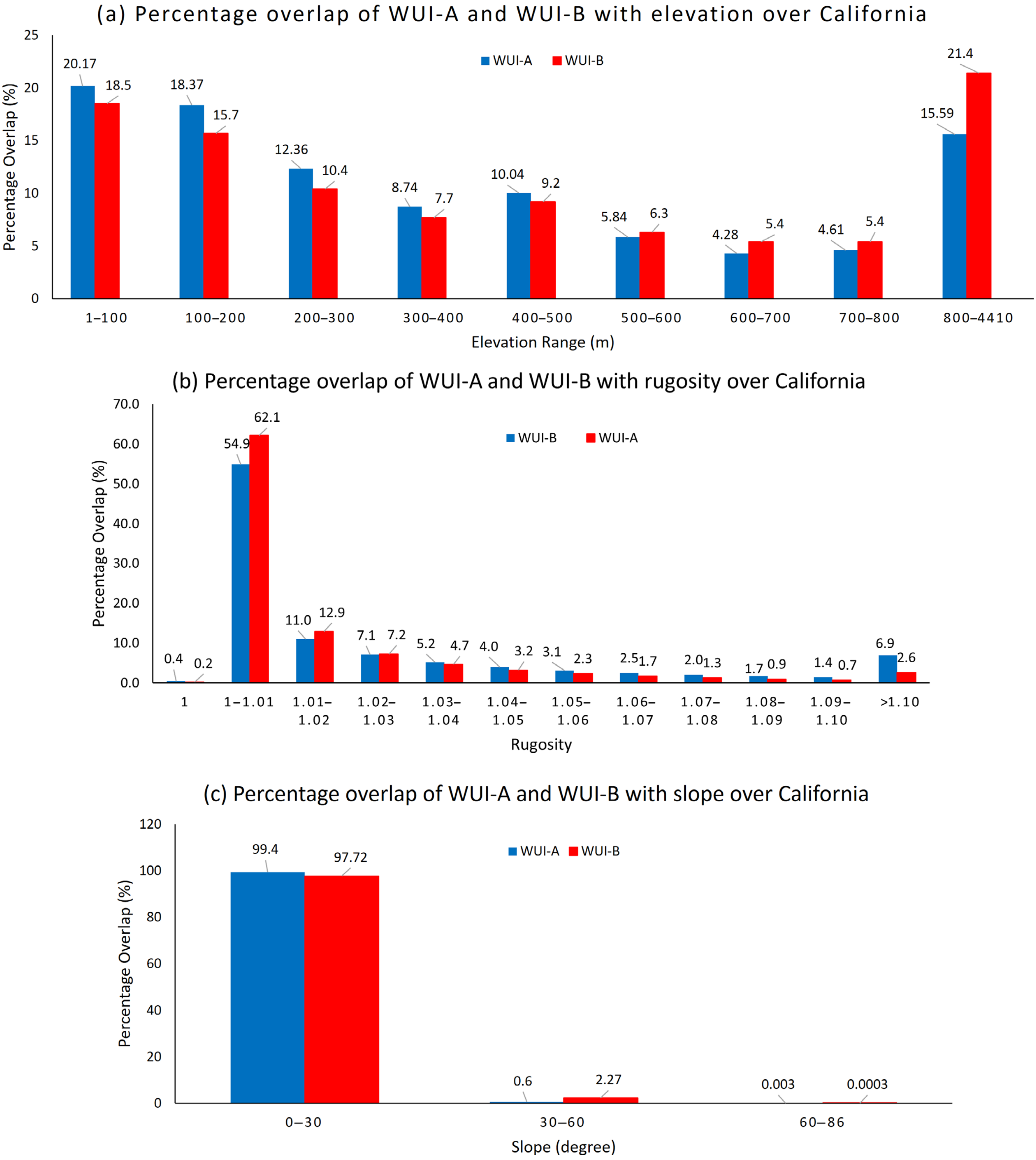
Slope and aspect

Figure S2c in Appendix S1 shows the spatial distribution of slope over California, and most of the regions are in the lower slope ranges. The percentage overlap of WUI-A (WUI-B) with the slope ranges 0–30, 30–60, and 60–86 of the state is 97.72% (99.4%), 2.27% (0.6%), and 0.0003% (0.003%), respectively, as can be seen in Figure 7c (Appendix S1: Table S5). The direction that a surface slope faces is called aspect and is defined as the angle between the positive *x*-axis and the projection of the normal onto the *x*, *y* plane. In Appendix S1: Figure S2d, the spatial variation of the aspect has been shown for California, and there is an almost similar distribution of the direction of the surface slopes as represented by the aspect in all the four quadrants. However, there is an almost similar distribution of the percentage overlap of WUI-A and aspect for California in the three quadrants, having first (23.82%), second (23.61%), fourth (23.4%), and with a little higher (29.17%) in the third quadrant (Figure 7d; Appendix S1: Table S6). Also, Figure 7d shows the percentage overlap of WUI-B and aspect for California, and it is highest in the second quadrant (30%), whereas the other three quadrants have 23.4% (first), 23.4% (third), and 23.1% (fourth), that is, almost equal percentages.

Importance of parameters in WUI definition to wildfires

Importance of current parameters to wildfire occurrence probability

The pair plots for current parameters in the WUI mapping definition are shown in Appendix S1: Figure S3. The red points represent wildfire ignition points, and the black points represent the random nonfire points. It shows intuitively that the distance to WUI areas and housing density have a significant correlation with wildfire occurrence: Both large and small wildfires tend to occur close to WUI areas; large wildfires were concentrated in nondeveloped areas, whereas small wildfires occurred at all housing density levels. To further understand the relationship between parameters in the WUI definition and wildfire occurrence probability, LoRs were fitted to each parameter as a function of wildfire occurrence probabilities. Due to the differences between large and small wildfires in Appendix S1: Figure S3, they were fitted separately. As shown in Figure 8, within WUI


(a) Percentage overlap of WUI-A and WUI-B with elevation over California

(b) Percentage overlap of WUI-A and WUI-B with rugosity over California

(c) Percentage overlap of WUI-A and WUI-B with slope over California

FIGURE 7 Histograms showing the percentage overlap of wildland–urban interface (WUI) for California with (a) different elevation ranges, (b) rugosity, (c) slope, and (d) aspect. Two colored columns are used to show the different WUI data sources used here for comparison: the red bars show the WUI data from Martinuzzi et al. (2015); the blue bars show data from the CAL FIRE (FRAP, 2015) WUI dataset.

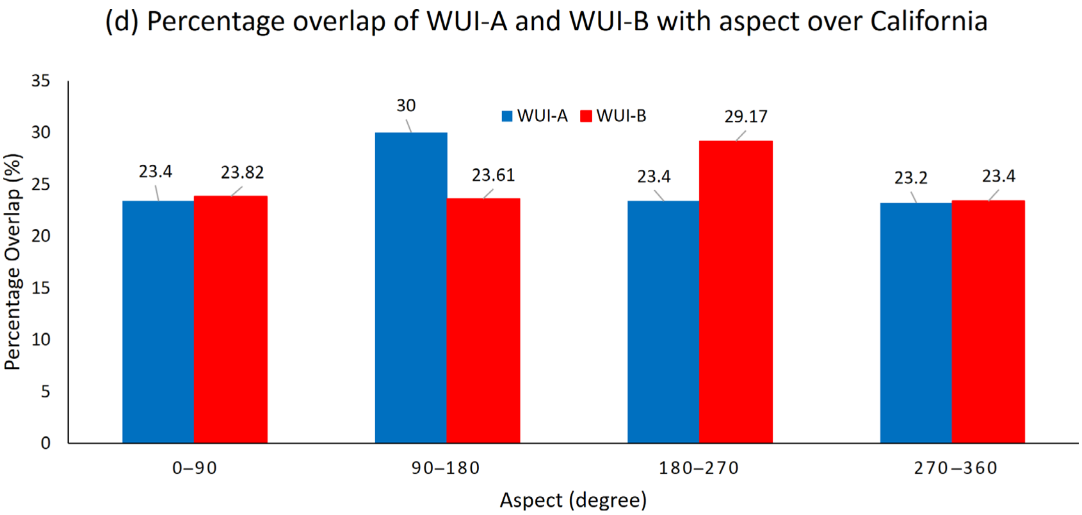


FIGURE 7 (Continued)

areas and within 10 km of the periphery, the occurrence probability of wildfires is higher than the threshold (0.5) and increases with the shortening of the distance. In terms of the housing density, large wildfires were most likely to occur in low-housing-density areas. The probability of fire occurrence decreases monotonously with the increase in housing density, and the housing density at the probability threshold is 252 houses/km^2. Although most small fires also occurred in relative nondeveloped areas, their occurrence probabilities are not stable, and there is no significant correlation with the housing density. The relationships between the occurrence probability of large and small wildfires and vegetation density are completely opposite. The occurrence probability of large wildfires increases monotonically as vegetation density increases, whereas the small wildfire occurrence probability decreases with the increase in vegetation density.

After analyzing the relationship between individual WUI parameters and wildfire occurrence, a LoR integrating all parameters was fitted to show the relative importance of parameters in the WUI definition in wildfire occurrence. The estimated coefficients in Table 2 show that for large wildfires, vegetation density contributes the most and has a positive correlation with occurrence probability. Distance to WUI and housing density have very little effect on large wildfires. However, in the small fires, distance to WUI areas contributes the most to their occurrence, followed by vegetation density. Housing density still has little effect on small wildfires.

Importance of WUI parameters in describing wildfire area

In the previous section, the estimated probability of large and small wildfires varies greatly with respect to the corresponding housing and vegetation density. Therefore, we changed the analysis object from the presence of wildfires to the area of wildfires and integrated all parameters to fit the linear model, so as to observe the changes in the importance of parameters. Due to the limitation of data, only large wildfire areas were analyzed here. The fitted linear model results are shown in Table 3. Both the vegetation density and the distance to WUI have a significant positive correlation with large wildfire areas. Wildfire area would increase with the increase in these two parameters. Thus, the distance to the WUI area has an impact on wildfire occurrence probability, but compared with vegetation density, its contribution can be ignored. However, when it comes to wildfire size, the effects of the distance to WUI areas are significant, and large wildfires tend to occur far away from the WUI area, which usually occurs deep in the forests or mountains. The impact of housing density on wildfire size is still negligible.

Importance of complex terrain on wildfires in WUI

Per results in WUI on the complex topography, the terrain in WUI is complex, which could also have an impact on wildfire occurrence. Thus, four topographic variables (elevation, aspect, slope, and rugosity) were fitted in the LoR as functions of wildfire occurrence probability and fire area to show how they relate. As shown in Table 4, the contributions of each parameter in the models for WUI-A and WUI-B are similar, especially for large wildfires. After adding terrain information, the contribution of rugosity to the large wildfire occurrence became prominent. Apart from rugosity, slope also contributes more to large wildfire occurrences compared to

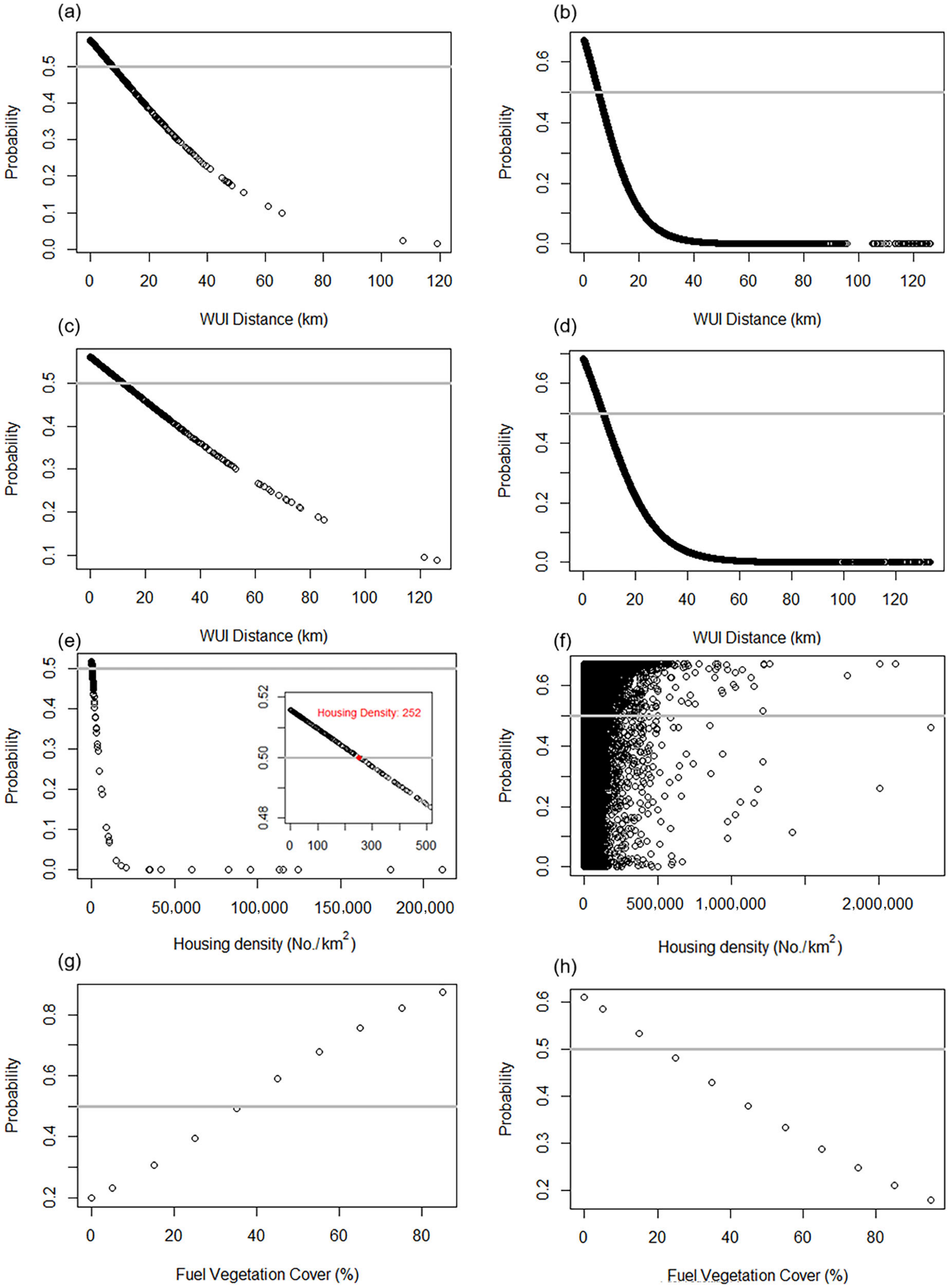


FIGURE 8 Probability curves for the occurrence of wildfires as a function of distance to wildland–urban interface (WUI), housing density, and vegetation density: (a) large wildfires, distance to WUI-A; (b) small wildfires, distance to WUI-A; (c) large wildfires, distance to WUI-B; (d) small wildfires, distance to WUI-B; (e) large wildfires, housing density; (f) small wildfires, housing density; (g) large wildfires, vegetation density; and (h) small wildfires, vegetation density.

TABLE 2 Results of logistic regression model for parameters in wildland–urban interface (WUI) definition and wildfire occurrence probability.

	Large wildfires				Small wildfires			
Parameter	**Estimate**	**SE**	***z***	**Pr(>|*z*|)**	**Estimate**	**SE**	***z***	**Pr(>|*z*|)**
WUI-A								
(Intercept)	−1.00000	0.17480	−5.72	0.00000	0.97320	0.01064	91.46	<2e-16
D2WUIA	−0.00003	0.00001	−3.11	0.00183	−0.13680	0.00121	−112.82	<2e-16
RhoHou	−0.00032	0.00013	−2.56	0.01021	0.00001	0.00000	40.02	<2e-16
FVC	0.03545	0.00370	9.59	<2e-16	−0.01663	0.00029	−57.53	<2e-16
WUI-B								
(Intercept)	−1.05100	0.17550	−5.99	0.00000	1.17000	0.01131	103.46	<2e-16
D2WUIB	−0.00002	0.00001	−2.62	0.00862	−0.10100	0.00087	−116.54	<2e-16
RhoHou	−0.00032	0.00013	−2.54	0.01102	0.00001	0.00000	29.32	<2e-16
FVC	0.03621	0.00368	9.84	<2e-16	−0.02119	0.00029	−73.62	<2e-16

Abbreviations: D2WUIA/D2WUIB, distance to WUI-A/WUI-B, the distance from fire and random nonfire points to WUI areas; FVC, fuel vegetation cover, the percentage cover of vegetation; RhoHou, housing density, the number of houses per square kilometer in each census block.

TABLE 3 Results of linear model for large wildfire area.

Parameter	**Estimate**	**SE**	***z***	**Pr(>|*t*|)**
WUI-A				
(Intercept)	−729.00000	3749.00000	−0.19400	0.84587
D2WUIA	199.30000	162.40000	1.22700	0.22012
RhoHou	0.00319	0.13560	0.02300	0.98126
FVC	292.40000	78.75000	3.71300	0.00022
WUI-B				
(Intercept)	−3393.00000	3786.00000	−0.89600	0.37000
D2WUIB	296.10000	119.10000	2.48700	0.01300
RhoHou	0.02858	0.13570	0.21100	0.83300
FVC	310.10000	78.05000	3.97200	0.00008

Abbreviations: D2WUIA/D2WUIB, distance to WUI-A/WUI-B, the distance from fire and random nonfire points to WUI areas; FVC, fuel vegetation cover, the percentage cover of vegetation; RhoHou, housing density, the number of houses per square kilometer in each census block; WUI, wildland–urban interface.

other parameters. In terms of small fires, distance to WUI is still the most prominent parameter in occurrence probability, followed by slope, vegetation density, and rugosity. The results from these two models illustrate that the complex topography within WUI has an impact on wildfire occurrence.

In addition to the above-mentioned estimates, the impact of parameters in the WUI definition and topographic parameters were explored by fitting a linear regression. The estimated results of models for WUI-A and WUI-B are still similar. Among all the parameters, rugosity affects the large wildfire area much more than other variables, followed by slope, distance to WUI, and vegetation density. It provides another confirmation of the influence of topography on the wildfires close to WUI. Comparing Tables 4 and 5, the distance to WUI, housing density, and elevation contribute to wildfires in different directions but to similar degrees.

CONCLUSIONS

Current wildland fire policy has placed a significant interest in the WUI areas, where increasingly more resources will be allocated for fire prevention, fuel treatment, home hardening against ignition, and general fire preparedness, such as removal of flammable materials around structures, as well as evacuation planning. In this work, we examine the modalities of WUI exposure to wildfires in California by comparing two preexisting

TABLE 4 Results of logistic regression model for parameters in wildland–urban interface (WUI) definition, topographic parameters, and wildfire occurrence probability.

	Large wildfires				Small wildfires			
Parameter	**Estimate**	**SE**	***z***	**Pr(>|*z*|)**	**Estimate**	**SE**	***z***	**Pr(>|*z*|)**
WUI-A								
(Intercept)	1.95514	2.81267	0.69500	0.48698	1.24000	0.02670	46.42	<2e-16
D2WUIA	−0.02901	0.00922	−3.14600	0.00165	−0.13610	0.00122	−111.35	<2e-16
RhoHou	−0.00028	0.00011	−2.52800	0.01149	0.00001	0.00000	39.28	<2e-16
FVC	0.02712	0.00397	6.83800	0.00000	−0.01520	0.00030	−51.29	<2e-16
ELE	0.00016	0.00011	1.51600	0.12944	−0.00036	0.00001	−34.43	<2e-16
ASP	0.00120	0.00069	1.73900	0.08209	0.00164	0.00006	27.12	<2e-16
SLP	0.05763	0.01944	2.96400	0.00304	−0.03489	0.00084	−41.71	<2e-16
RUGO	−3.54702	2.82999	−1.25300	0.21007	0.01077	0.02318	0.46	0.642
WUI-B								
(Intercept)	1.76137	2.81130	0.62700	0.53097	1.43800	0.02540	56.62	<2e-16
D2WUIB	−0.02017	0.00660	−3.05700	0.00223	−0.10070	0.00088	−115.03	<2e-16
RhoHou	−0.00029	0.00011	−2.53500	0.01125	0.00001	0.00000	28.62	<2e-16
FVC	0.02733	0.00396	6.90700	0.00000	−0.01981	0.00029	−67.18	<2e-16
ELE	0.00020	0.00011	1.78900	0.07355	−0.00035	0.00001	−34.15	<2e-16
ASP	0.00130	0.00069	1.89800	0.05764	0.00168	0.00006	27.43	<2e-16
SLP	0.05641	0.01945	2.90100	0.00372	−0.03532	0.00085	−41.68	<2e-16
RUGO	−3.38495	2.83051	−1.19600	0.23174	0.00563	0.02127	0.26	0.791

Abbreviations: ASP, aspect; D2WUIA/D2WUIB, distance to WUI-A/WUI-B, the distance from fire and random nonfire points to WUI areas; ELE, elevation; FVC, fuel vegetation cover, the percentage cover of vegetation; RhoHou, housing density, the number of houses per square kilometer in each census block; RUGO, rugosity; SLP, slope.

definitions of WUI with respect to past wildfire events. We specifically asked the following four questions. (1) Where are the wildfires (a) igniting and (b) burning relative to the WUI? (2) What is the impact of buffer distance on the percentage overlap of fire perimeters and fire ignition points in the WUI? (3) Where is the WUI located in terms of elevation and the complexity of the terrain? (4) What is the relative importance of WUI parameters that impact wildfire occurrence and size within or near the WUI?

It was found that a very small percentage of wildfire-burned areas were within the WUI areas. Additionally, only a very few numbers of wildfires were ignited within WUI areas. However, when we introduce a buffer distance from the existing WUI perimeters, there is a significant increase in the percentage of wildfire events in terms of fire ignition points. More than 50% of wildfire events occurred at a buffer distance of 5 km from the existing WUIs. This shows that not only WUIs are the zones of wildfire occurrence, but also the non-WUI or areas larger than the existing WUI (extended WUI) are highly prone to wildfires. Our results highlight a rapid rate of increase in the percentage overlap of wildfire-burned areas and fire ignition points in the extended WUIs.

The buffer distance analysis shows the importance of considering spotting fire behavior when considering fire risk in the WUI. Although the actual fire front might not burn significantly within the WUI areas, firebrands and burning embers originating from the fire front might travel these buffer distances and, under favorable conditions, might be able to ignite structures (Storey et al., 2020). Anecdotal evidence of unburnt and unconsumed trees adjacent to destructed structures in the WUI during high-intensity fires (such as Paradise, California, during the Thomas Fire, 2018) bears evidence of these effects. WUI areas do not need to see a "tsunami or flood of flames," rather they are at a higher risk from firebrand ignitions, which have also been reported in Wildfire Today (2020).

The topography of a landform plays an important role, and knowing the location of existing WUIs relative to topographic factors would give us a better understanding of fire dynamics and allow us to plan adequate firefighting strategies. This study highlights that a

TABLE 5 Results of linear model for parameters in wildland–urban interface (WUI) definition, topographic parameters, and large wildfire area.

Parameter	Estimate	SE	*z*	*t*
WUI-A				
(Intercept)	4684.000	64,760.000	0.072	0.94235
D2WUIA	311.800	123.400	2.526	0.01169
RouHou	0.020	0.136	0.146	0.88382
FVC	232.800	85.860	2.711	0.00682
ELE	−1.452	2.526	−0.575	0.56557
ASP	23.990	15.580	1.540	0.12395
SLP	328.300	452.900	0.725	0.46865
RUGO	−11,360.000	65,150.000	−0.174	0.86161
WUI-B				
(Intercept)	4684.000	64,760.000	0.072	0.94235
D2WUIB	311.800	123.400	2.526	0.01169
RouHou	0.020	0.136	0.146	0.88382
FVC	232.800	85.860	2.711	0.00682
ELE	−1.452	2.526	−0.575	0.56557
ASP	23.990	15.580	1.54	0.12395
SLP	328.300	452.900	0.725	0.46865
RUGO	−11,360.000	65,150.000	−0.174	0.86161

Note: See Table 4 for abbreviation explanations.

significant portion of the existing WUI in California is on complex topography, where the meteorological factors, like wind speed, are more favorable for a higher rate of fire spread and increased spotting distances, and firefighting is difficult due to complex terrain.

Last but not the least, we also studied the relative importance of WUI parameters in explaining wildfire occurrence and wildfire areas in the WUI. The density of vegetation in the WUI was found to be strongly related to both the occurrence and areas of large wildfires (>400 ha or 1000 acres), whereas the distance between the wildfire ignition points and the WUI was found to be most significant in describing the occurrence of smaller wildfires (<400 ha or 1000 acres). When including topographic parameters, surface roughness and slope play a significant role in describing the occurrence and burned areas of large wildfires. On the other hand, topography plays a less dominant role in explaining the occurrence of smaller wildfires compared to the distance to WUI areas. The two existing maps of WUI in California are not found to be significantly different when it comes to the relative importance of WUI parameters in determining wildfire occurrence or burned areas; however, they have different sensitivities in the context of buffer distance or overlaps with previous wildfire events and their relative proportions of interface and intermix areas.

This analysis can provide context while planning fuel treatment and home hardening projects and resource allocation for wildfire preparedness in the WUI areas in the state of California and elsewhere.

AUTHOR CONTRIBUTIONS

Mukesh Kumar: Conceptualization, methodology, software, data curation, writing—original draft preparation, visualization, investigation, software, validation, writing—reviewing and editing. **Shu Li**: Methodology, software, data curation, writing—reviewing and editing, visualization. **Phu Nguyen**: Methodology, software. **Tirtha Banerjee**: Conceptualization, supervision, reviewing and editing, project administration, funding acquisition.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data are already published and publicly available, with those publications cited in this article.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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